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Searches for extra dimensions with the ATLAS and CMS detectors

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Abstract

Models with extra spatial dimensions have been proposed to explain the large apparent hierarchy between the Electroweak and Planck scales. Such models predict a host of different new phenomena observable at the energy scale in reach with the LHC. Searches for these phenomena with the full 8 TeV LHC dataset taken with the ATLAS and CMS detectors are presented for different topologies. The exchange of gravitons propagating through the extra dimensions can lead to resonant or non-resonant enhancements in high mass tails. Semi-classical and quantum black holes could form and their decays provide for different spectacular signatures.

Keywords: Extra Dimensions, Microscopic Black Holes, Exotic search, ATLAS, CMS, LHC

1. Introduction

One of the open questions of modern particle physics is the so-called "Hierarchy problem". The heaviest particles of the Standard Model, like the $W^{\pm}$, Z or Higgs bosons live at the *Weak Scale* of $M_{\rm EWK} = 0.264\,$TeV, the vacuum expectation value of the Higgs field. In contrast there is a huge gap to the *Planck Scale* of $M_{\rm Pl} \sim 10^{16}\,$TeV, which is believed to be the scale, where gravity becomes strong and Quantum effects important. A consequence of this large hierarchy is the apparent weakness of Gravity in our world as compared to the Electroweak or Strong interactions. There are many attempts of finding a natural explanation for the large scale difference without resorting to *fine tuning*.

One class of solutions challenges our fundamental understanding of the four-dimensional space-time by postulating *extra spacial dimensions*. The weakness of gravity follows then from its propagation through these extra dimensions, making it appear weak in our SM brane. These new dimensions obviously need to possess special properties, as the experimental evidence for the four-dimensional space-time is overwhelming at macroscopic length scales. Two generic models are usually considered:

- The *Large Extra Dimension* model following Arkani-Hamed, Dimopoulos, Dvali (ADD) [1, 2], where n compact, extra dimensions with a radius R are considered. The *true Planck Scale* is then assumed to be equal to the weak scale, $M_{\rm D} = M_{\rm EWK}$, thus removing the hierarchy problem. The *observed Planck Scale* $M_{\rm Pl}$ is then related to the true one as
$$M_{\rm Pl}^2 \sim M_{\rm D}^{2+n} R^n \,.$$
These extra dimensions are *large* in the sense, that the size R could be at the order of $\sim 1\,$mm to $1\,\mu$m.

- The *Warped Extra Dimension* model following Randall and Sundrum (RS) [3]: through the special curvature of the extra dimension gravity is suppressed exponentially by a *warp factor*
$$\Lambda_\pi \sim M_{\rm Pl} e^{-kR\pi} \,,$$
thus reducing the large scale difference by the exponential of a (relatively) small number kR.

Both of these models make specific predictions for new phenomena observable at the energy scale of the LHC.

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The first class of observations is related to the propagation of *Gravitons* through the compact extra dimensions, so-called *Kaluza-Klein* (KK) excitations. The virtual exchange of these states would appear as massive new resonances, which could be resolved, narrow resonances in the case of the RS theory, or a succession of many narrow-spaced resonances, leading to a broad excess as in the ADD model. In case of the direct production of the KK excitations these would escape undetected into the extra dimensions, leaving a large momentum imbalance in the event, so-called *mono X signatures*, where *X* could be a jet or a photon for example.

In the case of the ADD model it is furthermore expected, that *microscopic black holes* should form, once available energy exceeds a certain threshold M_{Thresh}, which will be above the $(4+n)$ dimensional Planck scale M_{D}, but typically far below M_{Pl}. The phenomenology of the two cases, production close to or far above threshold, must be distinguished. In case of the production happening far above threshold, the black hole would undergo a high-multiplicity decay via Hawking Radiation (*semi-classical* case). For a production near threshold, it is conjectured, that a *Quantum Black Hole* could form, which would decay to two-body final states. While there is no actual resonance involved, the production close to threshold dictates a *quasi-resonant* final state with a visible enhancement at a certain invariant mass.

In the following the state of the search for signatures inspired by *Extra Dimensions Models* will be briefly reviewed. Most of the analyses on the full Run 1 dataset of pp collision data at $\sqrt{s}$ = 8 TeV with an integrated luminosity of 20 fb^{-1} delivered by the LHC [4] to the ATLAS [5] and CMS [6] experiments are now completed.

2. High mass di-lepton searches

The final state of two high $p_T \gtrsim 25 \ldots 40$ GeV isolated leptons (e^+e^- or $\mu^+\mu^-$) are part of the standard search repertoire at hadron colliders. The Standard Model background is dominated by the Drell-Yan process, which theoretically well understood. The analyses then proceed to search an excess above the background in the high invariant mass region $m_{\ell\ell} \gtrsim 1$ TeV. Both narrow resonances (RS G^*) [7, 8] and non-resonant excess generated by ADD KK graviton excitations [9–11] have been searched for. In Fig. 1 an example experimental di-electron invariant mass spectrum is shown. Both experiments exclude extra dimensions up to *string scales* $M_S = 2\sqrt{\pi}[\Gamma(n/2)]^{1/(n+2)} M_D \sim 6 \ldots 3$ TeV depending on the number of extra dimensions n and model details, as can be seen in Fig. 1 for some examples.

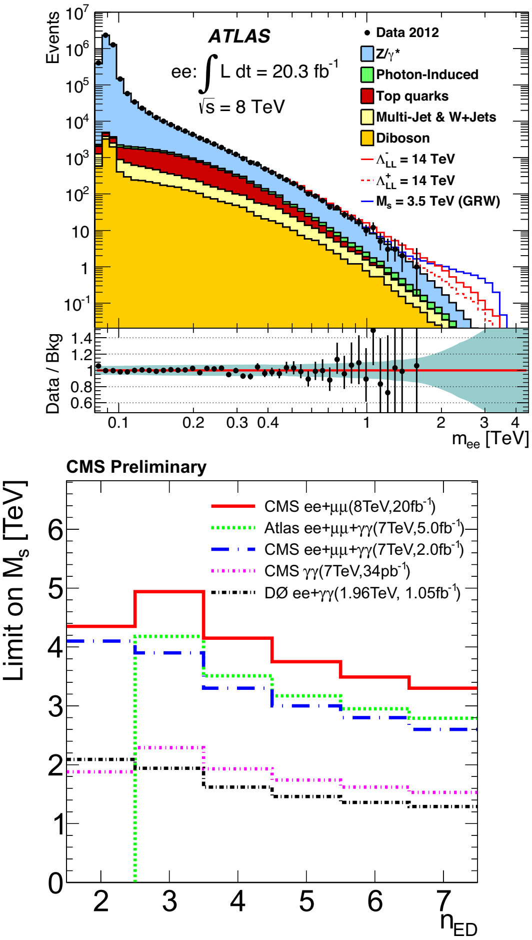

Figure 1: Top: Example di-electron invariant mass spectrum together with several model expectations for non-resonant high mass enhancements [9]. Bottom: No significant excess above background has been observed, thus limits are set on the number of extra dimensions and string scales [11].

The same topology of a non-resonant excess at high di-lepton invariant mass has also been used to place limits on contact interactions [9, 12], pushing the new physics scales as high as $\Lambda \gtrsim 15 \ldots 25$ TeV.

3. Mono Photons and Mono Jets

The direct production of gravitons followed by their escape into the extra dimensions leads to signatures with single high $p_T \gtrsim 150$ GeV objects, like photons [13] or jets [14], accompanied by large missing transverse momentum $\not{E}_T$. The SM backgrounds are dominated by Z boson production in association with a photon or a jet, followed by an invisible $Z \to \nu\nu$ decay. In Fig. 2 the observed distribution of the missing transverse momentum in the $\gamma + \not{E}_T$ search is shown. Also here limits are set on ADD model parameters like the number of extra dimensions. The exclusion limits in the jet + $\not{E}_T$ channels, shown in Fig. 2, are more stringent with $M_D \gtrsim 5\ldots3$ TeV.

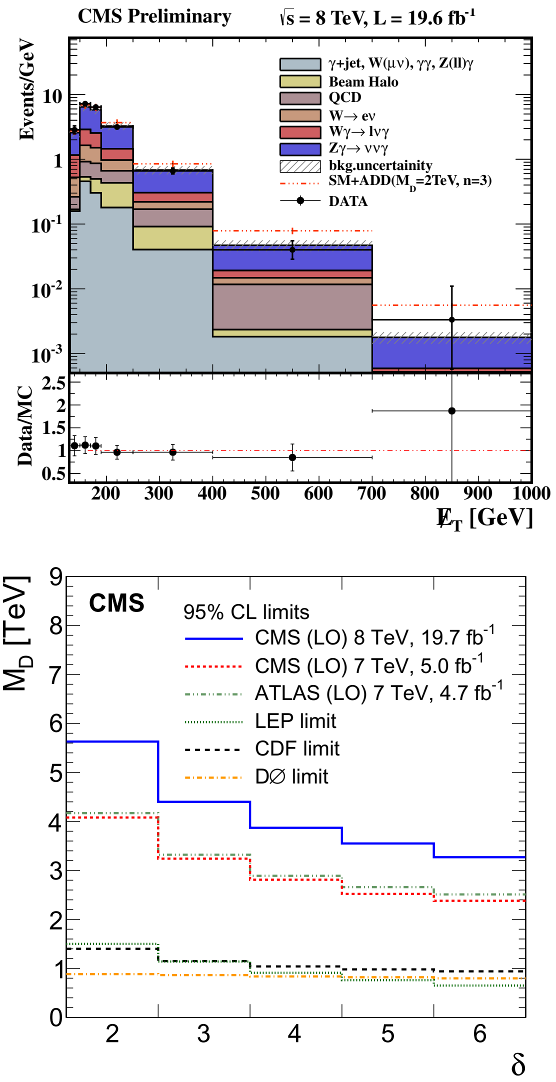

Figure 2: Top: Observed distribution of the missing transverse momentum in the $\gamma+\not{E}_T$ search [13]. Bottom: Exclusion limits on Planck Scale M_D as a function of number of extra dimensions obtained in the in the jet + $\not{E}_T$ [14].

4. Semi-classical Black Holes

Semi-classical Black Holes are those created with sufficient energy above the $n + 4$ dimensional Planck mass M_{D}. They are expected to thermalise and then undergo decay via Hawking radiation to a high-multiplicity final state of different high p_T objects. The models guiding the search and used to set exclusion limits, implemented for example in the BlackMax or Charybdis generators, leave a certain freedom in simulating the details of initial energy loss, rotation properties, and the evaporation of remnant. The parameter space of these models is explored to some extend.

Searches are typically carried out requiring at least 2 or 3 high $p_T \gtrsim 50\ldots100$ GeV objects, which can be either leptons and/or leptons, sometimes also photons and $\not{E}_T$ in addition. The region sensitive to semi-classical black hole production is the region of high object multiplicity and high $S_T = \sum p_T$ computed over all considered objects. In the multi-jet dominated selection [15] the SM background was derived from low multiplicity regions. In contrast, for the lepton+jets selection [16] the background is dominated W, Z or $t\bar{t}$ production and modelled from MC simulation scaled in signal-free control regions. In Fig. 3 the observed $\sum p_T$ distributions a high multiplicity dominated multi-jet dominated and a lepton+jet signal selection are shown. As no excess above the background expectation is observed, exclusion limits on the threshold for black hole production have been set, which are typically in the region of $M_{\mathrm{Thresh}} \lesssim 6\ldots4.5$ TeV depending on the above mentioned model details.

Other searches use specific final states with low SM backgrounds, like same-sign di-muons $\mu^{\pm}\mu^{\pm}$. Also here no excess has been observed and limits have been set [17] .

5. Quantum Black Holes

As no signs of extra dimensions have been observed so far, it is natural to assume, that the available production energy of so far less than $\sqrt{s} = 8$ TeV is at best close to threshold, $M_{\mathrm{Thresh}} \sim M_{\mathrm{D}}$ for black hole production. In this case the above discussed semi-classical phenomenology is not expected to be valid any more [18]. Instead, a created *Quantum Black Hole* (QBH) will not thermalise and rather decay to a low multiplicity state, typically just two particles. Because of the dominance of the threshold region, a *quasi-resonant* behaviour is expected, where the invariant mass of the two decay products has a significant enhancement near M_{Thresh}.

Following this arguments, any search combining two high p_T objects and searching for a quasi-resonant enhancement at high invariant mass may be used to discover QBHs. Many of the classical di-object searches for high mass resonances can be re-interpreted in terms

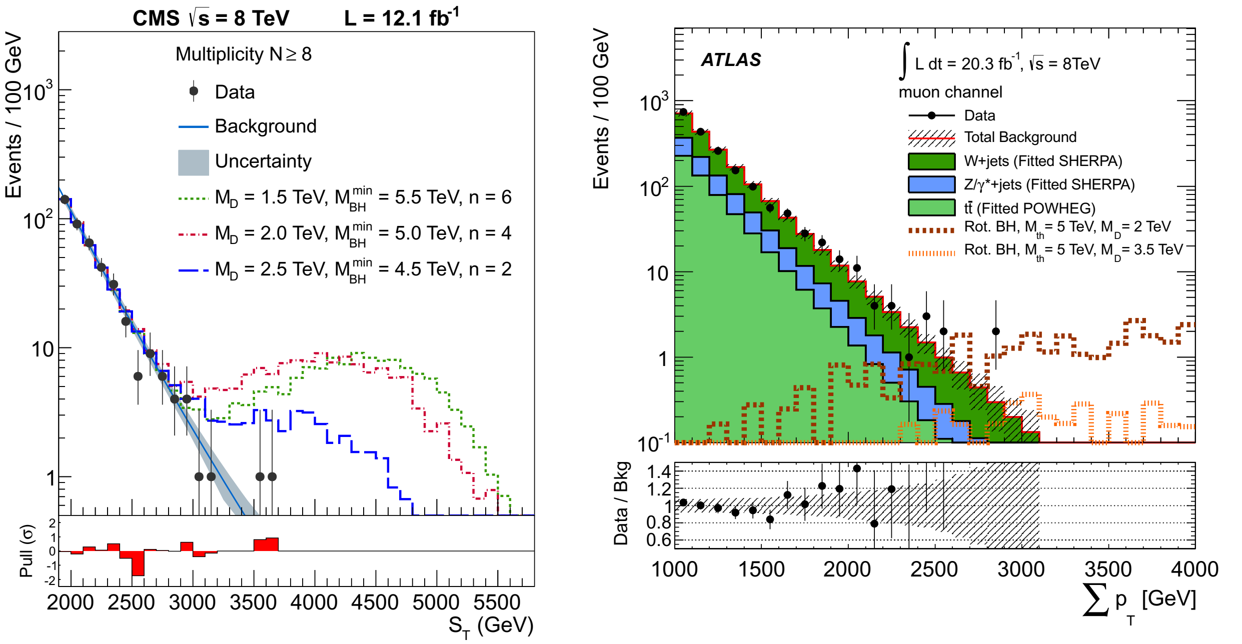

Figure 3: Left:: $S_T = \sum p_T$ of a multi-jet dominated high multiplicity search region with at least eight high p_T objects [15]. Right: $\sum p_T$ distribution of a lepton+jet dominated search [16].

of QBH models. The following final states have been considered:

- a dedicated search in the lepton plus jet channel with $p_T > 130$ GeV [19], where the background dominated by W + jets events, see Fig. 4;
- photon plus jet channel with $p_{T,\gamma} > 125$ GeV [20], where the dominant SM t-channel background can be suppressed by requiring a central photon and a small rapidity separation from the jet;
- the di-lepton $\ell^+\ell^-$ channel [7], as discussed already in Sec. 2,
- the di-jet resonance analysis [21] as well as the multi-jet search in the low multiplicity region [15].

As none of these searches have observed a significant excess, limits on QBH production are set. In the QBH production local quantum numbers like colour and charge are conserved and thus the favoured final states are of the di-jet topology. Consequently, the di-jet searches set the most stringent limit at the level of $M_{\text{Thresh}} \gtrsim 5.5$ TeV for ADD QBH production with $n = 6$ extra dimensions and $M_{\text{Thresh}} = M_{\text{D}}$, see Fig. 4.

6. Conclusions

Theories with extra dimensions provide a possible solution to the *Hierarchy Problem* and predict new physics near the *Electroweak scale* of ~ 1 TeV. Thus, the new phenomena are expected to be observable at the LHC. Many analyses on the full 8 TeV dataset of 20 fb^{-1} are now completed and so far no signs of physics beyond the Standard Model have been found. The typical exclusion ranges of the new physics scale is in the range of $\sim 2 \ldots 6$ TeV. However, the physics models for extra dimensions have significant degrees of freedom. Starting in 2015 the LHC is expected to deliver pp collisions at a significantly higher centre of mass energy of $\sqrt{s} = 13$ TeV, which will enhance the production cross section for high mass states of $m > 3$ TeV by large factors of at least 10. Therefore with the coming data most of the favoured parameter space of Extra Dimension Models will be thoroughly tested.

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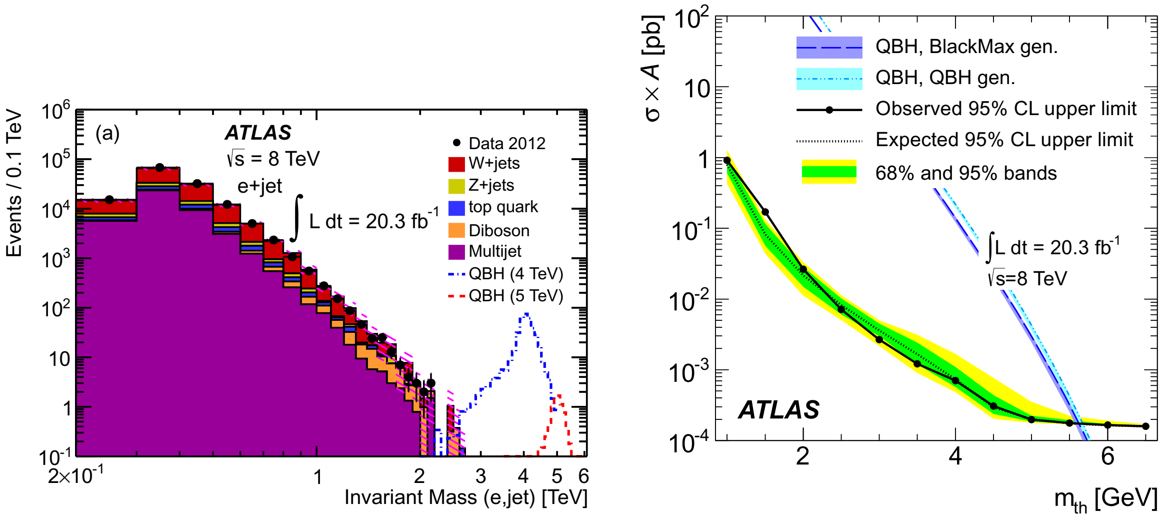

Figure 4: Left: the observed lepton+jet invariant mass spectrum of a dedicated QBH search [19]. Right: Expected and observed limits on production cross section times acceptance in the di-jet resonance search as a function of QBH production threshold M_{Thresh} together with two model expectations [21].

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